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Climate change as an intergenerational problem

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Predicting climate change is a high priority for society, but such forecasts are notoriously uncertain. Why? Even should climate prove theoretically predictable—by no means certain—the near-absence of adequate observations will preclude its understanding, and hence even the hope of useful predictions. Geological and cryospheric records of climate change and our brief recent record of instrumental observations show that the climate system is changeable on all time scales—from a few years out to the age of the earth. Major physical, chemical, and biological processes influence the climate system on decades, centuries, and millennia. Glaciers fluctuate on time scales of years to centuries and beyond. Since the Industrial Revolution, carbon dioxide has been emitted through fossil fuel burning, and it will be absorbed, recycled, and transferred amongst the atmosphere, ocean, and biosphere over decades to thousands of years.

As in most scientific problems, no substitute exists for adequate observations. Without sufficient observations, useful prediction will likely never be possible. Models will evolve and improve, but, without data, will be untestable, and observations not

taken today are lost forever. The great difficulty facing scientists trying to understand and predict the system is the extremely limited duration over which even marginally adequate observations of the climate system exist.

The thermometer was not invented until the early 17th century. Atmospheric observations did not approach global coverage until the end of the Second World War. Oceanic observations became marginally adequate on a global scale only in the early 1990s. Mass-balance data for the Greenland and Antarctic glaciers began in the early 21st century. Paleo data do provide records for some variables (e.g., global average CO₂ concentrations from ice cores), but are rough proxies having only limited precision and spatial coverage for the space and time scales of interest.

Few scientists would expect to understand any but the most trivial physical phenomenon without having observed its variation on all-important time scales. Oceanic surface waves have dominant periods not much different than one second. A suggestion that such a phenomenon could be understood from one second or less of observations would be greeted with ridicule.

Scientists trying to understand the climate system are faced with the difficult problem of making sense of physical phenomena whose time scale exceeds both professional and human life spans. Proposals for geo-engineering must include an understanding of their influence on a system that retains memories of induced disturbances for thousands of years. Who would claim to understand the impact of a major perturbation to the climate system based upon 10 years of data?

Understanding of climate change is a problem for multiple generations. One generation of scientists has to make provisions for the needs of successor generations, rather than focusing solely on its own immediate scientific productivity. Today's climate models will likely prove of little interest in 100 years. But adequately sampled, carefully calibrated, quality controlled, and archived data for key elements of the climate system will be useful indefinitely.

This intergenerational problem must be faced by any entity—government or otherwise—hoping to eventually provide accurate forecasts of climate change. Weather forecasting and national weather services are often invoked as the analogue for climate problems. But long-duration observations require a very different approach than do those of near-term interest, such as in weather prediction. Many examples exist where attempts to use weather data as records of climate have proved ambiguous at best and useless at worst, because of inadequate calibration, poor documentation of calibrations, temporal gaps, and undocumented and/or poorly understood technology changes. The use of radiosonde humidity sensors is a case in point: Technology changes and differences among nations seriously compromise the use of such weather data for climate studies (1). Thompson et al. (2) show how difficult the interpretation is of such a seemingly simple data set as sea surface temperature.

Government agencies can do a reasonable job in satisfying the immediate needs of the public, e.g., in forecasting hurricane trajectories. But governments have not



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Remote weather station in Iceland.

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done well in sustaining long-term observations. For example, the iconic time series of CO₂ observations at Mauna Loa, HI, was funded in 2-year increments for decades and was nearly terminated many times by shortsighted program managers (3).

Designing, maintaining, and coping with the technical evolution of climate observations is an extremely difficult problem requiring deep insight into the nature of the problem, and of the available and potentially available technologies. It cannot be sensibly done within a system funded year-by-year; it requires an agency with a long view—decades and beyond—a requirement that is alien to governments. Yearly budget battles put all programs at risk: Having a climate observing system started by one administration and disassembled by another, one political cycle later, is fatal.

In many cases—describing and understanding decadal variability in the ocean, for example—an honest scientific assessment would acknowledge the need for far longer observational records than are now available or obtainable by any individual. In today's institutions with their short-term time horizons, young scientists interested

in such phenomena cannot take on long-term problems. But if society does not find ways to support scientific careers directed at such problems, then we will never understand the fundamentals of this critical subject. What to do?

A few examples exist of comparatively long-lived, nominally focused organizations (universities, a few banks, some religious foundations). Although their true intellectual continuity is highly debatable, they do suggest the possibilities for the creation of a useful intergenerational climate-study infrastructure. Some components of astronomy and perhaps, uniquely, the Rothamsted Research agricultural station in the United Kingdom, are conceivable analogues. Elsewhere (4), we have outlined a possible approach, one that requires a private endowment to sustain the best sci-

entists and engineers willing to devote a portion of their time to overseeing the data streams that future generations of scientists will need. Other means may exist to sustain scientifically and technically competent organizations over decades and longer. Methods must be found—perhaps in public, private, national, and international institutional partnerships—that can isolate core observations from the vagaries of year-to-year government funding decisions and that can provide oversight of calibrations, management of shifting technologies, and understanding so as to avoid obsolescence and quality loss.

Without confronting the problem as an intergenerational one, climate forecasts and our ability to mitigate and adapt to climate change will remain rudimentary and inadequate for the challenges that lie ahead.

1 Elliott WP, Gaffen DJ (1991) On the utility of radiosonde humidity archives for climate studies. *Bull Amer Meteor Soc* 72(10):1507–1520.

2 Thompson DW, Kennedy JJ, Wallace JM, Jones PD (2008) A large discontinuity in the mid-twentieth century in observed global-mean surface temperature. *Nature* 453(7195):646–649.

3 Keeling CD (1998) Rewards and penalties of monitoring the earth. *Annu Rev Energy Environ* 23:25–82.

4 Baker DJ, Schmitt RW, Wunsch C (2007) Endowments and new institutions for long-term observation. *Oceanography* 20(4):10–14.